(12)

AD________

REPORT NO M24/80

Predicting Sweat Loss Response
To Exercise, Environment and Clothing

U S ARMY RESEARCH INSTITUTE
OF
ENVIRONMENTAL MEDICINE
Natick, Massachusetts

July 1980

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER M24/80	2. GOVT ACCESSION NO. AD-A113508	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Predicting Sweat Rate Response to Exercise, Environment and Clothing		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER M24/80
7. AUTHOR(s) Yair Shapiro, Kent B. Pandolf and Ralph F. Goldman		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 3E162777A845
11. CONTROLLING OFFICE NAME AND ADDRESS Same as 9. above		12. REPORT DATE 13. NUMBER OF PAGES 24
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLAS 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

sweat loss; required evaporative cooling; maximal evaporative capacity; humid and dry heat; heat transfer; clothing insulation and permeability; metabolism; heart rate; skin temperature; rectal temperature.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Metabolic heat production (M), clothing heat transfer characteristics, and the environment dictate a required evaporative cooling (E_{req}) from the body to maintain thermal balance. However, the maximal evaporative capacity (E_{max}) is dictated by vapor transfer properties of the clothing and environment. Relationships between metabolic load, environmental conditions, clothing and sweat loss were studied in 34 heat acclimatized males categorized into 4 groups (8, 8, 8 and 10 subjects) and exposed to various environmental conditions (T_a, 20 - 54°C, and rh, 10 - 90%), (cont'd)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLAS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

levels of metabolic rate (resting; walking 1.34 $m \cdot s^{-1}$, level; and walking 1.34 $m \cdot s^{-1}$, level; and walking 1.34 $m \cdot s^{-1}$, 5% grade) while wearing various clothing ensembles (shorts and T-shirts, fatigues, fatigues plus overgarment, and sweat suit). Each group was not exposed to all combinations. Exposures lasted 120 min: either 10 min rest, 50 min exercise, 10 min rest, 50 min exercise, or 120 min at rest. Physiological measurements included heart rate, rectal temperature, mean skin temperature, energy expenditure and sweat loss ($\dot{m}_{sw}$). E_{max} and E_{req} were calculated from environmental conditions, metabolism, clothing insulation and permeability. The ratio E_{req} to sweat rate was found to correlate with E_{max} and not with M. The predictive equation for sweat rate was: $\dot{m}_{sw} = 27.9 \cdot E_{req} \cdot (E_{max})^{-0.455}$; $g \cdot m^{-2} \cdot h^{-1}$ within the limits: $50 < E_{req} < 360$; $20 < E_{max} < 525$, $W \cdot m^{-2}$. This formula predicts sweat loss under different work loads and climates.

Eur J Appl Physiol (1982) 48: 83–96

European Journal of
Applied Physiology
and Occupational Physiology

Predicting Sweat Loss Response to Exercise, Environment and Clothing

Y. Shapiro, K. B. Pandolf, and R. F. Goldman

Military Ergonomics Division, U.S. Army Research Institute of Environmental Medicine, Natick, MA 01760, USA

Summary. Metabolic heat production (M), clothing heat transfer characteristics, and the environment dictate a required evaporative cooling (E_{req}) from the body to maintain thermal balance. However, the maximal evaporative capacity (E_{max}) is dictated by vapor transfer properties of the clothing and environment. Relationships between metabolic load, environmental conditions, clothing and sweat loss were studied in 34 heat-acclimatized males categorized into four groups (eight, eight, eight, and ten subjects) and exposed to various environmental conditions (ambient temperature, 20–54° C, and relative humidity, 10–90%), three levels of metabolic rate (resting; walking $1.34\ m \cdot s^{-1}$, level; or walking $1.34\ m \cdot s^{-1}$, 5% grade) while wearing various clothing ensembles (shorts and T-shirts, fatigues, fatigues plus overgarment, or sweat suit). Individual groups were not exposed to all combinations. Exposures lasted 120 min: either 10 min rest – 50 min exercise – 10 min rest – 50 min exercise, or 120 min at rest. Physiological measurements included heart rate, rectal temperature, mean skin temperature, energy expenditure and sweat loss (Δm_{sw}). E_{max} and E_{req} were calculated from environmental conditions, metabolism, clothing insulation and permeability. The ratio $E_{req}/\Delta m_{sw}$ was found to correlate with E_{max} and not with M. The predictive equation for sweat loss was: $\Delta m_{sw} = 18.7 \times E_{req} \times (E_{max})^{-0.455}$ within the limits $50 < E_{req} < 360$; $W \cdot m^{-2}$ and $20 < E_{max} < 525$; $W \cdot m^{-2}$. This formula predicts sweat loss for specific work loads, climates and clothing ensembles.

Key words: Sweat loss – Required evaporative cooling – Maximal evaporative capacity – Humid and dry heat – Heat transfer

Introduction

Metabolic heat production (M) and heat exchange with the environment by radiation and convection (R + C) determine the required evaporative cooling

Offprint requests to: Kent B. Pandolf, PhD (address see above)

0301-5548/82/0048/0083/$ 02.80

(E_{req}) to maintain thermal balance. Most of this cooling must come from sweat, since, in man, respiratory evaporation contributes only to a minor degree in warm or hot environments. Thus, if secreted sweat is 100% effective for dissipating body heat, the sweat rate (converted to evaporative rate) would equal E_{req}, assuming no body heat storage.

For 100% effectiveness of sweating, all sweat must be evaporated at the skin. When air vapor pressure (P_a) is low, as in hot-dry environments, the maximum evaporative capacity of the environment (E_{max}) for a nude man will far exceed E_{req}, the percent skin wetted area will be low (Gagge 1937), and the secreted sweat will be totally effective for cooling. However, as air vapor pressure increases (humid conditions), the skin vapor pressure (P_{sk}) must increase correspondingly to maintain the same evaporation rate, and wetted area increases. After skin relative humidity reaches 100% (skin totally wetted), a further rise in air vapor pressure causes evaporative cooling to fall below E_{req}, and body heat storage occurs (Woodcock and Breckenridge 1965). Various authors have found that sweat efficiency falls below 100% when the skin is only partially wetted; some sweat apparently drips from the skin since the sweat rate exceeds that needed to provide E_{req}. Candas et al. (1979) found a decrease in efficiency when skin wettedness exceeded 74%. Givoni (1963) found this threshold when E_{req} was above 20% of E_{max} (corresponding to a 20% skin wettedness). Kerslake (1963), working with a vertical cylinder, observed dripping when the cylinder was 45% wetted. Mitchell et al. (1976) showed in addition that the amount of unevaporated sweat under humid conditions varied with the degree of heat acclimation and the time into an exposure.

Since core temperature and skin temperature are the main inputs to the thermoregulatory center, and the sweat glands are major thermoregulatory effectors in hot environments, the sweat glands will receive more impulses with increases in heat production or storage (Bligh 1978; Houdas et al. 1978), and inhibitory feedback as a result of skin wettedness and decreases in skin temperature (Bullard et al. 1967; Candas et al. 1979; Kerslake 1972; McCallrey et al. 1979). It can be assumed, therefore, that sweat production should be correlated with E_{req} (heat production and R + C heat exchange), and with the maximal evaporative capacity of the environment which, as originally defined by Gagge (1937), together with the actual evaporative heat loss (E_{sk}) dictates the wettedness of the skin (E_{sk}/E_{max} determines skin wettedness).

The three main attempts previously reported to predict sweat rate are based on the above assumptions. The predicted 4 h sweat rate index (P4SR) (Macpherson 1960) which is derived from the nomogram for the basic 4 h sweat rate (B4SR) involves air temperature, wet-bulb temperature, air speed and a correction for the type of clothing. These factors are used for determining the E_{max} and then subsequently the B4SR from which the P4SR is calculated taking into consideration the metabolic rate (the major contributor to E_{req}). The prediction equation by Givoni and Berner-Nir (1967) is based on an exponential function of the ratio E_{req}/E_{max}. Lustinec's equation and nomogram (1973) are based on the linear correlation between sweat rate and E_{req} for low skin wettedness, but use a non-linear correlation between sweat rate, E_{req} and E_{max} when the skin wettedness is high. The above equations and nomograms are not

Table 1. The physical characteristics of the subjects (mean ± SE)

Series	Group	Age (year)	Weight (kg)	Height (cm)	Body surface area (m^2)	Body fat (%)
1	1	22.1 ± 1.0	71.3 ± 4.4	176.4 ± 4.0	1.87 ± 0.07	18.3 ± 1.7
1	2	21.8 ± 0.8	72.8 ± 3.0	173.2 ± 2.3	1.86 ± 0.05	18.7 ± 1.4
1	3	22.1 ± 0.6	72.9 ± 3.4	177.4 ± 2.3	1.90 ± 0.05	14.9 ± 1.1
2	–	21.1 ± 0.6	75.6 ± 4.2	178.6 ± 2.1	1.93 ± 0.06	17.7 ± 1.6
3	–	20.9 ± 0.6	75.3 ± 5.5	178.2 ± 2.5	1.93 ± 0.07	17.3 ± 1.9

totally comprehensive. The P4SR is limited to air temperatures above 27° C and to low relative humidity. Givoni and Berner-Nir's equation is limited to $E_{req}/E_{max} < 1$, and Lustinec's equation to E_{req} lower than 100 $W \cdot m^{-2}$ when E_{max} is lower than 100 $W \cdot m^{-2}$, and to E_{req} lower than 300 $W \cdot m^{-2}$ when E_{max} is lower than 200 $W \cdot m^{-2}$.

The purpose of this study was to develop a comprehensive mathematical prediction equation of sweat loss for a wide range of environmental conditions, energy expenditures and clothing ensembles. The intended use of this equation is to help predict the water requirements of military and industrial personnel to replace water secreted in sweat.

Methods

Thirty-four male volunteer soldiers served as subjects. All subjects were fully informed with regard to experimental risk and gave their written informed consent. The experiments were divided into three series, with the first series composed of three groups of eight subjects each, the second series of ten subjects, and the third of eight subjects who had participated also in the second series. The physical characteristics of the subjects are summarized in Table 1.

Prior to the heat exposures, all subjects underwent medical examination to determine their fitness for the study. The thirty-four subjects, dressed in T-shirts, shorts, socks, and indoor shoes, were then acclimatized for 6 consecutive days by walking on a level motor-driven treadmill at 1.34 $m \cdot s^{-1}$ for two 50 min periods with both a preceding and intervening 10 min rest period, at 49° C, 20% relative humidity (rh), 1 $m \cdot s^{-1}$ wind speed. No significant changes were found for rectal temperature, mean skin temperature or heart rate during the last two days of this acclimatization period. After this acclimatization period, the subjects were exposed to the various environmental, exercise and clothing variations as described in Tables 2 and 3.

Each exposure lasted 120 min: 10 min rest – 50 min walk – 10 min rest – 50 min walk, or 120 min continuous rest for the resting group. During all heat exposures, rectal temperature (T_{re}) was recorded from a Y.S.I. rectal thermistor probe inserted ~10 cm beyond the anal sphincter. Skin temperatures were monitored with a three-point thermocouple skin harness (chest, calf, and forearm) and mean weighted skin temperature ($\bar{T}_{sk}$) was calculated according to Burton (1935). Using a Hewlett-Packard 9825A Calculator and 9862A Plotter on line during experimentation, both $\bar{T}_{sk}$ and T_{re} were plotted for each subject at approximately 2 min intervals. Heart rate was measured by radial artery palpation during the rest periods and after each 25 min of walking. Ad lib. water drinking was encouraged. At the end of the first rest period and at the end of each walking period, two-min expired air samples were collected in Douglas bags. The volume was measured in a Collins Spirometer and converted to standard environmental conditions (STPD), and the O_2 and CO_2 concentrations were measured with an Applied Electrochemistry Model S-3A O_2 analyzer and Beckman LB-2 infrared CO_2 analyzer. A time-weighted average metabolic rate (M) was calculated

Table 2. Environmental conditions, exercise intensity, E_{req}, E_{max}, measured and predicted sweat loss (mean ± SE) in the first series of the present study, and comparisons with three other methods of prediction

Number of subjects	Clothing	T_a (°C)	rh (%)	Walking speed ($m \cdot s^{-1}$)	Treadmill grade (%)	E_{req} ($W \cdot m^{-2}$)	E_{max} ($W \cdot m^{-2}$)	Sweat loss ($g \cdot m^{-2} \cdot h^{-1}$)	$E_{req}/\Delta m_{sw}$	Predicted sweat loss ($g \cdot m^{-2} \cdot h^{-1}$)			
										Present study	Lustinec	Givoni	P4SR
First series													
8	Fatigue	35	75	Rest	–	61 ± 4	133 ± 1	198 ± 15	0.47 ± 0.02	184	120	105	132
6	Fatigue	35	75	1.34	0	185 ± 5	158 ± 1	580 ± 31	0.49 ± 0.04	517	400	314	550
8	Fatigue	35	75	1.34	5	201 ± 6	163 ± 1	691 ± 41	0.44 ± 0.02	654	480	341	660
7	Shorts	35	75	Rest	–	66 ± 5	188 ± 1	164 ± 16	0.62 ± 0.04	179	150	113	92
8	Shorts	35	75	1.34	0	169 ± 5	193 ± 2	386 ± 23	0.67 ± 0.04	431	370	289	450
8	Shorts	35	75	1.34	5	197 ± 5	202 ± 2	556 ± 43	0.55 ± 0.04	493	400	336	560
7	Fatigue	40	32	Rest	–	100 ± 4	286 ± 2	217 ± 14	0.70 ± 0.03	213	180	173	204
8	Fatigue	40	32	1.34	0	220 ± 4	329 ± 3	480 ± 24	0.70 ± 0.03	441	380	378	455
8	Fatigue	40	32	1.34	5	251 ± 5	347 ± 3	517 ± 27	0.73 ± 0.03	491	415	430	566
7	Fatigue	49	20	1.34	0	293 ± 8	333 ± 2	581 ± 15	0.76 ± 0.03	584	500	501	620
8	Shorts	40	32	Rest	–	114 ± 5	358 ± 3	206 ± 16	0.86 ± 0.05	220	210	198	158
8	Shorts	40	32	1.34	0	228 ± 4	409 ± 3	401 ± 15	0.86 ± 0.02	414	340	392	421
8	Shorts	40	32	1.34	5	244 ± 3	427 ± 3	465 ± 19	0.80 ± 0.03	434	400	420	395
4	Shorts	49	20	1.34	0	302 ± 10	408 ± 6	507 ± 51	0.91 ± 0.07	549	470	518	580
8	Shorts	49	20	1.34	5	340 ± 5	433 ± 3	599 ± 31	0.87 ± 0.04	601	530	582	690

Table 3. Environmental conditions, exercise intensity, E_{req}, E_{max}, measured and predicted sweat loss (mean ± SE) in the second and third series of the present study, and comparisons with three other methods of prediction

Number of subjects	Clothing	T_a (°C)	rh (%)	Walking speed ($m \cdot s^{-1}$)	Treadmill grade (%)	E_{req} ($W \cdot m^{-2}$)	E_{max} ($W \cdot m^{-2}$)	Sweat loss ($g \cdot m^{-2} \cdot h^{-1}$)	$E_{req}/\Delta m_{sw}$	Predicted sweat loss ($g \cdot m^{-2} \cdot h^{-1}$)			
										Present study	Lustinec	Givoni	P4SR
Second series													
8	Fatigue	40	30	1.34	0	222 ± 2	325 ± 4	390 ± 19	0.85 ± 0.04	460	380	381	410
8	Sweat suit	37	80	Rest	–	78 ± 4	20 ± 1	556 ± 52	0.22 ± 0.02	558	[a]	125	210
7	Sweat suit	37	80	1.34	0	206 ± 4	32 ± 1	932 ± 88	0.35 ± 0.04	1190	[a]	315	1100
5	Fatigue and overgarment	37	80	1.34	0	197 ± 6	92 ± 2	849 ± 64	0.34 ± 0.02	714	[a]	328	1100
8	Fatigue	37	80	1.34	0	192 ± 4	120 ± 2	767 ± 51	0.39 ± 0.03	617	500	323	1100
8	Shorts	22	30	1.34	0	73 ± 6	448 ± 10	126 ± 15	0.93 ± 0.11	127	100	127	[a]
8	Shorts	40	30	1.34	0	213 ± 5	234 ± 2	670 ± 45	0.49 ± 0.03	606	425	364	450
Third series													
10	Shorts	49	20	1.34	0	297 ± 5	439 ± 6	502 ± 19	0.90 ± 0.03	522	460	510	605
10	Shorts	54	10	1.34	0	362 ± 4	525 ± 7	586 ± 23	0.94 ± 0.03	586	530	621	710
10	Shorts	37	80	1.34	0	188 ± 4	137 ± 3	560 ± 27	0.51 ± 0.02	561	500	318	1040
10	Shorts	20	40	1.34	0	52 ± 4	439 ± 9	95 ± 13	0.91 ± 0.06	91	90	90	[a]
10	Shorts	41	80	Rest	–	106 ± 2	40 ± 2	584 ± 48	0.28 ± 0.02	560	[a]	175	790
10	Shorts	35	90	1.34	0	173 ± 4	116 ± 3	554 ± 41	0.49 ± 0.04	556	500	292	1040
10	Shorts	49	20	1.34	5	350 ± 7	405 ± 9	646 ± 32	0.82 ± 0.02	637	550	598	724
10	Shorts	49	20	1.34	0	309 ± 5	424 ± 7	516 ± 13	0.90 ± 0.02	551	480	530	620

[a] Out of the range of the model

as 0.17 (= 20 min/120 min) of the resting value plus 0.83 (= 100 min/120 min) of the mean of the two level walking values. In the case of walking uphill, the external work was deducted from the measured metabolic rate (Pandolf et al. 1977). Total body weight losses were determined from pre- and post-walk nude measurements on a K-120 Sauter precision electronic balance (accuracy of ± 10 g) for calculation of sweat loss. Sweat loss was determined from weight loss, adjusted for water intake and urine output. The sweat rate was expressed as the theoretical evaporative cooling power (Δm_{sw}) (1 watt = 1.486 g · h^{-1}), and normalized per m^2 surface area.

The radiative and convective heat exchange with the environment (R + C), the evaporative cooling power needed to maintain thermal equilibrium (E_{req}) and the maximal evaporative cooling power of the environment (E_{max}) were calculated according to Givoni and Goldman (1972, 1973) using the actual $\bar{T}_{sk}$ for the $T_a - \bar{T}_{sk}$ gradient and P_{sk} for calculation of E_{max}. E_{req} and E_{max} were normalized per m^2 surface area.

The values for insulation (clo) around the man (*total* clo as measured by heated copper manikin) were 0.74, 0.99, 1.50, and 1.20 for shorts and T-shirt, fatigues, fatigues plus overgarment and plastic sweat suit respectively. The corresponding values for the evaporative coefficient of the clothing (i_m/clo) were 0.94, 0.75, 0.51, and 0.20 respectively. Criteria for terminating any heat exposure were a heart rate of 180 beats · min^{-1} during exercise, or of 140 beats · min^{-1} during rest, and/or a T_{re} above 39.5° C, dizziness, nausea, or dry skin.

Statistical Treatment

The differences in $E_{req}/\Delta m_{sw}$ were analyzed by using a mixed-factorial analysis with each subject receiving all combinations of factors (clothing and environmental conditions), but where the subjects were divided into groups by level of metabolism (rest, walking level and walking upgrade). If a significant F-value was found ($p < 0.05$), critical differences were calculated by Tukey's procedure to locate the significant mean differences. The power curve fit ($y = ax^b$) was calculated as a linear regression of the logarithmic expression $\ln y = \ln a + b \cdot \ln x$. In a similar way the exponential curve fit ($y = ae^{bx}$), the logarithmic curve fit ($y = a + b \cdot \ln x$), the parabolic curve fit ($y = a + bx + cx^2$), and $y = a + b/x$, $1/y = a + b/x$ and $y = a + b\sqrt{x}$ were all examined, as well as the associated linear regressions.

Results

Development of the Basic Sweat Loss Prediction Equation

Analysis of the 111 exposures from the first series of experiments (Table 2) yielded a similar $E_{req}/\Delta m_{sw}$ index ($p > 0.05$) for the same combinations of clothing and environmental conditions (similar E_{max}), regardless of the level of energy expenditure (different E_{req}). However, the index was different and highly significant ($p < 0.001$) for different E_{max} either when the change in E_{max} was a result of different environmental conditions (humid vs dry) or due to different clothing ensembles (change in i_m/clo). The relationship between $E_{req}/\Delta m_{sw}$ and E_{max} for these data of the first experimental series was found to be $E_{req}/\Delta m_{sw} = 0.0530\ E_{max}{}^{0.452}$ ($r = 0.87$) when E_{req}, E_{max} and the rate of sweat loss were expressed in W · m^{-2} (see Fig. 1, 2). It can be seen that the above mathematical formula used to express these data appears to be accurate for both the individual and the group responses in this first series of experiments.

The rate of sweat loss can be derived from the above as:

$$\Delta m_{sw} = 19 \times E_{req} \times (E_{max})^{-0.452};\ W \cdot m^{-2}$$

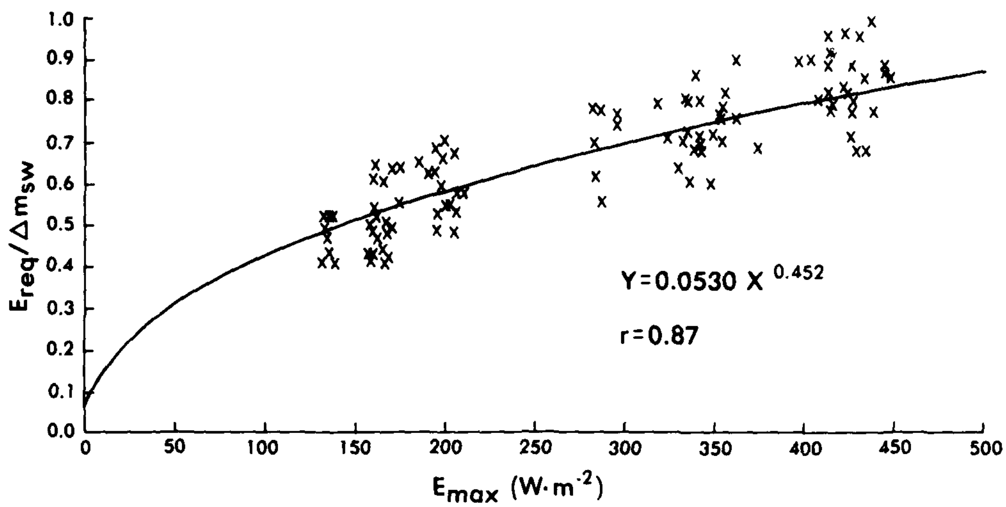

Fig. 1. Relationship between $E_{req}/\Delta m_{sw}$ and E_{max} derived from the first series *(individual points)*

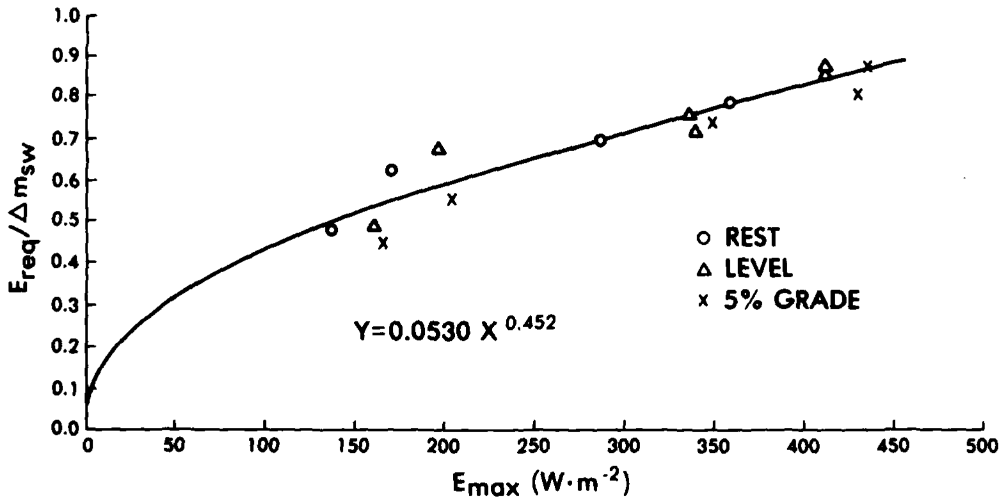

Fig. 2. Relationship between $E_{req}/\Delta m_{sw}$ and E_{max} for the three groups of the first series *(each point is an average of the group for each condition)*

limited to the ranges $135 < E_{max} < 430$ and $60 < E_{req} < 340$; $W \cdot m^{-2}$. The correlation between the predicted and the measured sweat loss for the first experimental series, over a wide range of sweating responses, was found to be $r = 0.94$, as illustrated in Fig. 3.

Expansion of the Basic Sweat Loss Prediction Equation

In the 132 exposures of the second and third series (Table 3), the equation was examined for a wider range of sweating responses than in the first series. High

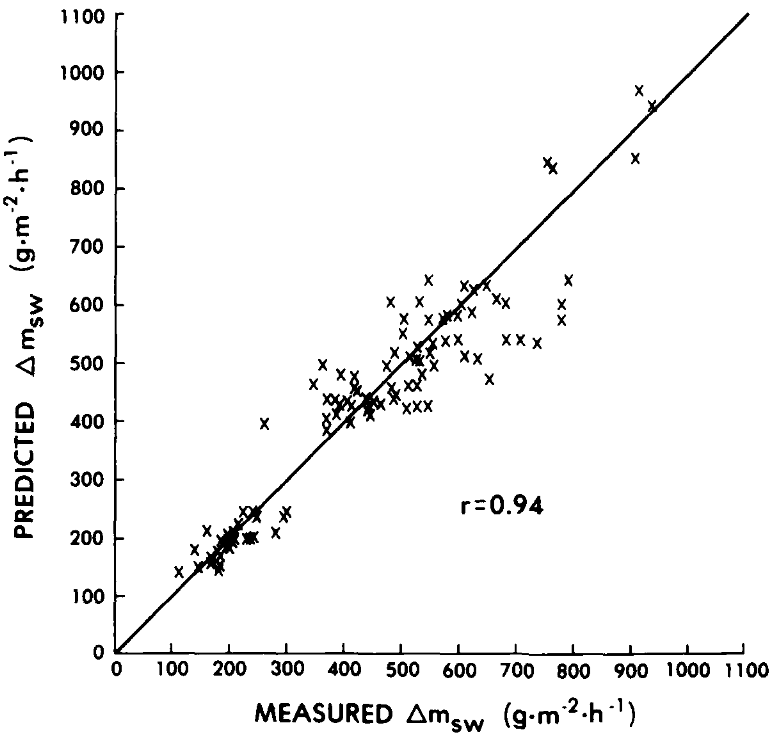

Fig. 3. Relationship between measured and predicted sweat loss for the first series *(individual points)*

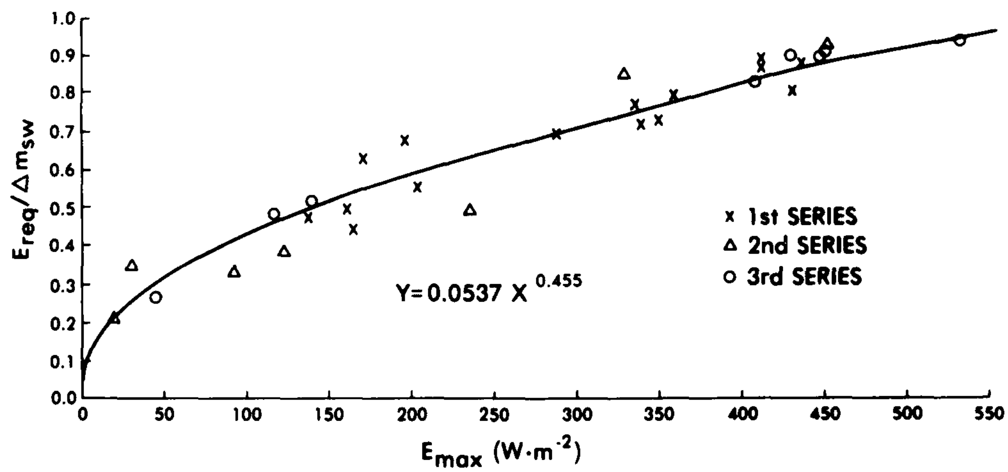

Fig. 4. Relationship between $E_{req}/\Delta m_{sw}$ and E_{max} for all three series of experiments *(each point is an average of a group in one condition)*

humidities and low permeable clothing (fatigue plus overgarment, and sweat suit) were used to challenge the equation in the low range of E_{max}, down to 20 $W \cdot m^{-2}$, and through the use of both a hot and very dry environment (49° C, 20% rh and 54° C, 10% rh) up to 525 $W \cdot m^{-2}$. Additional challenges were imposed when the E_{req} was reduced to 52 $W \cdot m^{-2}$ by exposure to a cool

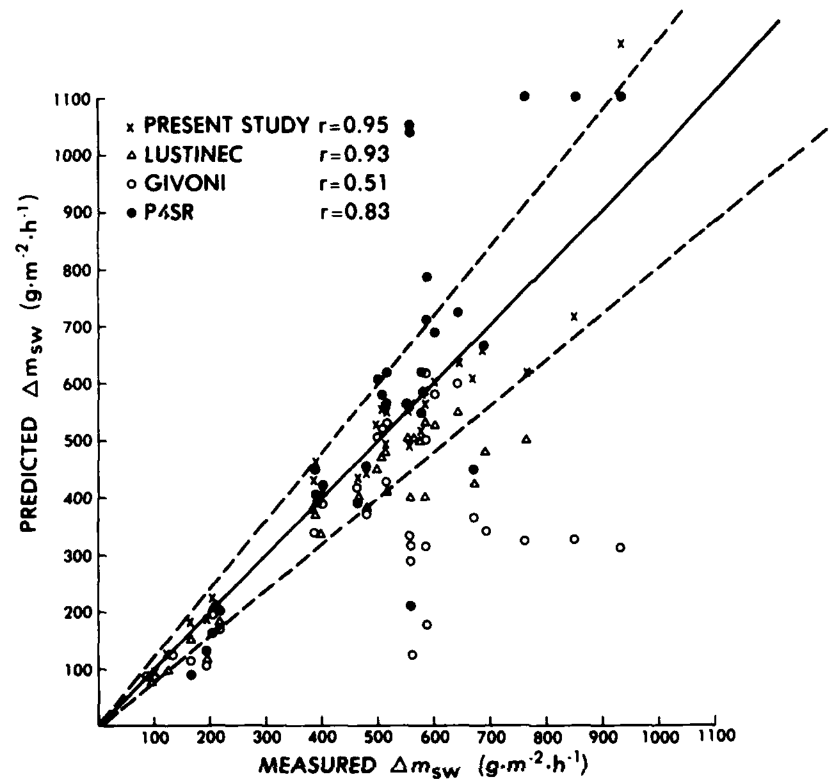

Fig. 5. Comparison of four methods for predicting sweat loss using the data from the present study. The solid line is the line of identity and the dashed lines represent the ± 20% range from this line of identity

environment (20° C, 40% rh), and to 78 $W \cdot m^{-2}$ by resting in an air temperature close to skin temperature. Expanding the limits of sweating responses in these ways yielded $E_{req}/\Delta m_{sw}$ values ranging from 0.22 ± 0.02 to 0.94 ± 0.03.

A comprehensive analysis of the relationship between $E_{req}/\Delta m_{sw}$ and E_{max} for all three experimental series left the original equation, derived from the first series, basically unchanged as illustrated in Fig. 4 ($E_{req}/\Delta m_{sw} = 0.0537\ E_{max}^{0.455}$; $r = 0.95$). Therefore,

$$\Delta m_{sw} = 18.7 \times E_{req} \times (E_{max})^{-0.455};\ W \cdot m^{-2}$$

bounded by the limits $50 < E_{req} < 360$; $W \cdot m^{-2}$ and $20 < E_{max} < 525$; $W \cdot m^{-2}$.

Comparison of the Present Prediction Equation with Other Predictive Methods

The measured values for sweat loss obtained in the present study were compared with values predicted from our data using Lustinec's (1973), Givoni and

Table 4. Comparison of the predicted sweat loss with the measured results of other investigators

	T_a (°C)	rh (%)	Experimental conditions			Sweat loss ($g \cdot m^{-2} \cdot h^{-1}$)	
			Wind speed ($m \cdot s^{-1}$)	Clothing	Effort	Measured	Predicted (Using present equation)
Macpherson (1960)	32	80	1.6	Shorts	Climbing 12″ bench 12 cycle · min^{-1}	186	178
	32	80	0.2	Shorts	Climbing 12″ bench 12 cycle · min^{-1}	256	241
	32	80	1.6	Shorts	Rest	65	73
	32	80	0.2	Shorts	Rest	71	102
	32	80	0.2	Overall	Rest	99	115
	32	80	1.6	Overall	Rest	76	80
	32	80	1.6	Overall	Climbing 12″ bench 12 cycle · min^{-1}	213	235
	49	25	0.5	Shorts	Climbing 12″ bench 12 cycle · min^{-1}	539	522
Givoni (1963)	35	23	2.0	Shorts	Rest	103	115
	36	88	2.0	Shorts	Rest	203	199
Candas et al. (1979)	48	33	E_{req} = 260 W; E_{max} = 260 W			305	420
Nadel and Stolwijk (1973)	36	65	15 min work 720 kpm · min^{-1} + 15 min rest			306	330
Gonzalez et al. (1978)	40	32	E_{req} = 193 $W \cdot m^{-2}$; E_{max} = 401 $W \cdot m^{-2}$			252	230

Berner-Nir's (1967), or Macpherson's (1960) P4SR method (Tables 2, 3, and Fig. 5). Using the present equation, only one condition (sweat suit, walking in 37° C, 80% rh), out of the 30 that were examined, resulted in a predicted sweat loss which differed by more than 20% from the measured. In the other 29 conditions, the predicted sweat loss was within the ± 20% range; the relationship found was: predicted Δm_{sw} = 3 + 0.98 measured Δm_{sw} (r = 0.95). With Lustinec's nomogram, eight conditions out of the 30 were out of the ± 20% range; in another four conditions, the sweat rate could not be predicted because the conditions were beyond the nomogram's range (see Table 3). Using the present data and Lustinec's method, it was found that the predicted Δm_{sw} = 46 + 0.72 measured Δm_{sw} (r = 0.93). For Givoni and Berner-Nir's equation, 14 conditions were out of ± 20% range; the prediction relationship using our sweat loss data and their method was Δm_{sw} = 151 + 0.38 measured Δm_{sw} (r = 0.51). The largest deviations from measured values using Givoni and Berner-Nir's equation were found when E_{req} was close to or above E_{max}. For the P4SR method the predicted sweat rate was beyond the ± 20% range in 12 instances, while in two other conditions the sweat rate could not be predicted because the conditions were out of the P4SR nomogram's range; it was found that predicted Δm_{sw} = −113 +1.34 measured Δm_{sw} with an r = 0.83.

Comparison of the Present Prediction Equation with Results of Other Authors

Comparison of the predicted sweat loss using the present equation with the measured data from various other studies (Table 4) shows that in most cases the present equation predicts sweat loss within the range of ± 20% (11 of 13 conditions). Exceptions involved the very low sweat rates found in the Royal Naval Tropical Research Unit experimental series (Macpherson 1960) (predicted 102 $g \cdot m^{-2} \cdot h^{-1}$ vs 71 measured), and a comparison where E_{req} equalled E_{max} (Candas et al. 1979).

Discussion

Physiological variables like core temperature, skin temperature and skin wettedness influence the rate of sweat loss (Benzinger et al. 1963; Bullard et al. 1967; Davies 1979; McCallrey et al. 1979). These variables, together with heat storage, metabolic rate and an internal set-point, can explain the different physiological models and pathways of sweat regulation (Benzinger et al. 1963; Houdas et al. 1978). Although these models are essential for understanding various thermoregulatory mechanisms, their applicability for prediction of sweat loss is limited because physiological measurements under actual exposures are needed to evaluate the predicted sweat loss. In our previous studies, it was shown that body temperatures and heart rate are predictable by comparing the demand for heat loss with the capacity for heat loss, using the two main variables of thermoregulation, the overall heat load (E_{req}) and the maximal evaporative cooling capacity of the environment (E_{max}) (Givoni and Goldman 1972, 1973). Since sweat loss depends on body temperatures, skin wettedness, metabolic rate (a determinant of E_{req}) and heat storage (a function of body temperatures) it can be assumed that the sweat loss can be derived directly from E_{req} and E_{max} without the need to measure the different physiological variables. The advantage of this assumption is obvious, because both E_{req} and E_{max} can be calculated directly from the environmental conditions, the predicted exercise intensity and the type of clothing without the need to make any physiological measurements. Thus, rate of sweat loss can be predicted (at least within ± 20%) without the need to make physiological measurements.

The theoretical need for sweat evaporative cooling is a linear function of E_{req} (sweat rate = $k^{-1} \cdot E_{req}$, where k is the latent heat evaporation of water). For a nude man, under conditions of low skin wettedness where the evaporation of sweat is practically unlimited, the sweat loss can be predicted using the above equation as was previously done by Lustinec (1973) for low skin wettedness. On the other hand, under other conditions where E_{max} is low or close to E_{req}, and the skin is wet, only part of the sweat is evaporated, while the rest of the sweat being produced is dripping or soaking the clothing, and therefore, the sweat rate will be higher than $k^{-1} \cdot E_{req}$. Because E_{max} is the major factor in determining the level of skin wettedness, it should be a part of any sweat loss prediction formula for clothed men or conditions of high skin wettedness.

In the present study, it was found that $E_{req}/\Delta m_{sw}$ was correlated with E_{max}. As expected, the ratio was high for high evaporative cooling capacity and low for low E_{max}. The relationship between the rate of sweat loss, E_{req} and E_{max} was found empirically to be: $\Delta m_{sw} = 18.7 \cdot E_{req} \cdot (E_{max})^{-0.455}$ with Δm_{sw}, E_{req} and E_{max} in $W \cdot m^{-2}$. For high E_{max} (dry skin), the above formula is very close to $m_{sw} = E_{req}$/latent heat, as expected. In contrast, the lower the E_{max}, the greater is its influence on the final values for the predicted sweat loss. For practical use (predicting water requirements), the formula can be converted to weight units ($g \cdot m^{-2} \cdot h^{-1}$) as follows: sweat loss = $27.9 \cdot E_{req} \cdot (E_{max})^{-0.455}$.

The present formula was derived from 250 exposures to a wide range of environmental conditions (cool, warm, hot, dry and humid) with a variety of clothing ensembles (light clothing, heavy clothing, high permeability and low permeability) and three different metabolic rates (rest, 300 and 450 W). Therefore, our prediction equation can be used for a wide range of E_{req} (50–360 $W \cdot m^{-2}$) and of E_{max} (20–525 $W \cdot m^{-2}$). Comparison of the estimates yielded by the present equation with measured values published by other investigators (Table 4) supports this suggestion. The main limitation for the present prediction equation appears to be at very high sweat rates. In this case, the formula appears to overestimate the rate of sweat loss; in one exposure in our study, when the measured sweat loss was 932 $g \cdot m^{-2} \cdot h^{-1}$, the predicted value was 1,190 (overestimation of 28%). In this condition, it can be assumed that the actual sweat rate was close to the maximal sweat rate, so the sweating mechanisms were saturated (Davies 1979) and the subjects could not "reach" the values predicted as required to achieve a steady state thermal equilibrium (Givoni and Goldman 1972, 1973).

In general, however, we suggest that sweat loss can be predicted simply as a function of E_{req} and E_{max} for a wide range of climatic conditions, clothing ensembles and metabolic rates. The present sweat loss prediction equation is more comprehensive than other existing methods because it allows for prediction over a wider range of total heat load (metabolic heat production and heat exchange with the environment), and evaporative cooling capacity with greater applicability to different clothing systems. The present formula predicts the rate of sweat loss more accurately than the other existing methods especially in extreme climatic conditions.

1. The views, opinons, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.
2. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

Acknowledgements. The authors wish to acknowledge the assistance of Ms. Ella H. Munro in the statistical analysis of the data, and Pat Basinger and Cynthia Bishop for their technical assistance in preparing the manuscript. A special thanks is due to Mr. John R. Breckenridge for his many helpful comments in editing the manuscript.

References

Benzinger TH, Kitzinger C, Pratt AW (1963) The human thermostat. In: Hardy JD (ed) Temperature: its measurement and control in science and industry, vol 3, part 3. Reinhold, New York, pp 637–665

Bligh J (1978) Thermoregulation: what is regulated and how? In: Houdas Y, Guieu JD (eds) New trends in thermal physiology. Masson, New York, pp 124–126

Bullard RW, Banerjee MR, MacIntyre BA (1967) The role of the skin in negative feedback regulation of eccrine sweating. In J Biometeorol 11:93–104

Burton AC (1935) Human calorimetry II. The average temperature of the tissue of the body. J Nutr 9:261–280

Candas V, Libert JP, Vogt JJ (1979) Human skin wettedness and evaporative efficiency of sweating. J Appl Physiol 46:522–528

Davies CTM (1979) Influence of skin temperature on sweating and aerobic performance during severe work. J Applied Physiol 47:770–777

Gagge AP (1937) A new physiological variable associated with sensible and insensible perspiration. Am J Physiol 120:277–287

Givoni B (1963) Estimation of the effect of climate on man: development of a new thermal index. Res Rep UNESCO Haifa: Israel Institute of Technology

Givoni B, Goldman RF (1972) Predicting rectal temperature response to work, environment, and clothing. J Appl Physiol 32:812–822

Givoni B, Goldman RF (1973) Predicting heart rate response to work, environment, and clothing. J Appl Physiol 34:201–204

Givoni B, Berner-Nir E (1967) Expected sweat rate as function of metabolism, environmental factors and clothing. Res Rep UNESCO Haifa: Israel Institute of Technology

Gonzalez RR, Berglund LG, Gagge AP (1978) Indices of thermoregulatory strain for moderate exercise in the heat. J Appl Physiol 44:889–899

Houdas Y, Lecroart JL, Ledru C, Carette G, Guieu JD (1978) The thermo-regulatory mechanisms considered as a follow-up system. In: Houdas Y and Guieu JD (eds) New trends in thermal physiology. Masson, New York, pp 11–19

Kerslake DMcK (1963) Errors arising from the use of mean heat exchange coefficients in the calculation of the heat exchanges of a cylindrical body in a transverse wind. In: Hardy JD (ed) Temperature: Its measurement and control in science and industry, vol 3, part 3. Reinhold, New York, pp 183–189

Kerslake DMcK (1972) The stress of hot environments. Cambridge University Press, London, pp 145–156

Lustinec K (1973) Sweat rate, its prediction and interpretation. Arch Sci Physiol 27: A127–A136

Macpherson RK (ed) (1960) Physiological responses to hot environments. Medical Research Council Special Report Series No. 298, Her Majesty's Stationery Office, London, pp 219, 294–299

McCallrey TV, Wurster RD, Jacobs HK, Euler DE, Geis GS (1979) Role of skin temperature in the control of sweating. J Appl Physiol 47: 591–597

Mitchell D, Senay LC, Wyndham CH, Van Rensburg AJ, Rogers GG, Strydom NB (1976) Acclimatization in a hot, humid environment: Energy exchange, body temperature, and sweating. J Appl Physiol 40: 768–778

Nadel ER, Stolwijk JAJ (1973) Effect of skin wettedness on sweat gland response. J Appl Physiol 35: 689–694

Pandolf KB, Givoni B, Goldman RF (1977) Predicting energy expenditure with loads while standing or walking very slowly. J Appl Physiol 43: 577–581

Woodcock AH, Breckenridge JR (1965) A model description of thermal exchange for the nude man in hot environments. Ergonomics 8: 222–235

Accepted July 9, 1981

DISTRIBUTION LIST

5 copies to:

US Army Medical Research and Development Command
HQDA
SGRD-RMS
Fort Detrick
Frederick, MD 21701

12 copies to:

Defense Technical Information Center
ATTN: DTIC-TCA
Alexandria, VA 22314

1 copy to:

Commandant
Academy of Health Sciences, US Army
ATTN: AHS-CDM
Fort Sam Houston, TX 78234

1 copy to:

Dir of Biol & Med Sciences Div
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

1 copy to:

CO, Naval Medical R&D Command
National Naval Medical Center
Bethesda, MD 20014

1 copy to:

HQ AFMSC/SGPA
Brooks AFB, TX 78235

1 copy to:

Director of Defense Research and Engineering
ATTN: Assistant Director (Environmental and Life Sciences)
Washington, DC 20301